DEVELOPMENT OF DETAILED FINITE ELEMENT MODELS OF CHILD RESTRAINT SYSTEMS FOR OCCUPANT PROTECTION

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ABSTRACT

A previously defined methodology for the development of Finite Element (FE) detailed models of road vehicles has been utilized to create four different FE models of Child Restraint Systems (CRS). The resulting CRS "fleet" includes two convertible toddler seats, one infant rear-facing seat and a booster seat. Model dimensions range from 5,865 nodes, 4,168 elements and 2 parts for the reduced booster seat to 18,204 nodes, 21,345 elements and more than 20 parts for the most complex convertible one. All adjustable reclining/rocking positions have been considered during the model definition. The main characteristics of the models, as well as the reverse engineering process, are discussed in this paper. Particular material properties have not been studied in depth, but some insight is also offered on this subject to the prospective analyst or modeler. Versatility of the models and future research work required to fully validate the models are briefly commented.

INTRODUCTION

Child safety in all road transportation modes is becoming a top-priority subject for both the regulatory and the research community, responding to a general demand stemming from the society itself. And it should not be otherwise considering in the first place that children are not yet responsible for their own choices and thus they should be provided under all circumstances with the maximum attainable level of safety. Not to mention, in the second place, the high level of protection of current CRS, with a fatal injury prevention potential of more than 70% for rear-facing infant seats and the almost complete absence of counter effects of CRS when properly used. Unfortunately, the misuse rate is certainly alarming, rising up to 80 % in the US [1].

In the USA, around 1,800 children under 14 are killed while travelling as occupants in motor vehicles and more than 280,000 are injured [2]. In Japan and only during 1998, 86 children under 16 died in the same tragic scenario [3]. With respect to Spain, just to add one more example, and in that same year 1998, 111 young passengers of light vehicles 15 year-old and younger died, 689 were seriously injured and another 3,627 sustained some kind of injury [4].

All those three countries have their own different crash test regulations for CRS. There are also specific CRS safety standards in Sweden and Australia/New Zealand. This circumstance may hinder the exchange of knowledge and experiences among the countries and therefore limit the protection currently offered to young occupants. While there are still some arguments against the harmonization of other types of safety regulations, like side impact, it can be stated as a general rule that those reasons do not apply to child safety restrain systems. CRS regulations are based on sled tests in a frontal or longitudinal configuration. Several research groups are currently working on an ISO proposal for side impact protection. Injury exposure during rollovers might become the next topic in child safety during the coming years. In USA and again in 1998, 351 children 12 year-old or younger died in crashes involving a rollover either as a first event or as a subsequent one [5]. In general, vehicle rollovers continue to be a relatively unexplored area with vast opportunities for improvement [6, 7, 8 and 9].

The use of Finite Element (FE) models in the field of automotive crashworthiness is a recent research area that enables advancements in transportation safety while reducing the normally considerable associated costs. Additionally, FE techniques can be used in the earliest phases of design to explore potential refinements, and performance in scenarios which differ from those originally intended to or even non-desired side-effects.

A methodology to develop detailed multi-purpose FE models of vehicles has been developed at validated at the National Crash Analysis Center (NCAC) during the last years. The NCAC is a research institute located near Washington DC, as a joint effort of the George Washington University, the Federal Highway Administration (FHWA) and the National Highway Traffic Safety Administration (NHTSA). Both the FHWA and the NHTSA are part of the US Department of Transportation.

The first FE models used for safety research consisted in the majority of cases of plain metal and structural components of vehicles. Other "soft" models have also been created worldwide in the recent years, included biomechanical individual systems, complete human surrogates and vehicle interiors. The FHWA/NHTSA NCAC has been also developing different models of vehicle interiors including seat belts, dashboard and airbag models [10, 11]. Main focus is directed normally to adult occupants. However, the same investigative philosophy can be applied to child occupant protection, an area where biomechanical and real-crash data are even scarcer.

Research in child occupant protection must always consider all injury risk abatement measures currently available, with special focus on restraint systems. Since adult seat belts are not designed for children, specially adapted protection devices, CRSs, are a necessity any time that they travel as occupants in fast-moving transportation modes: road vehicles as well as in the aviation ambit. Broad discussion in now open in the latter field, and some work has also been conducted [12]. Some simple models of CRS have been developed for use in rigid body simulation software, and even some optimization research has been performed [13]. However, in order to obtain the maximum benefit from the research potential of FE techniques and its coupling options with other simulation software such as MADYMO [14], detailed models of CRSs are required.

Since the Japan Automobile Research Institute (JARI) is currently conducting research on child protection, including both physical and numerical or virtual testing, and since no FE detailed models of CRSs were easily available to the research community so far, it was considered of interest to develop a series of FE models of various CRS to support on-going research. In particular, four models were created corresponding to two convertible CRS, an infant forward facing CRS and a booster seat.

REVERSE ENGINEERING METHODOLOGY

Reverse engineering can be defined as the collection of techniques utilized to recreate the original specifications out of a totally finished product. On the contrary, classic engineering develops a product starting from the original specifications. The term specification includes geometric and material data, as well as mass properties and part connections.

The basics of the Reverse Engineering process used for this research were developed at the FHWA/NHTSA National Crash Analysis Center by Schinke and improved by Zaouk [15, 16]. This methodology has been used, for instance, to create a detailed FE model of a Dodge Grand Caravan [17, 18]. Outside the NCAC, authors have already used similar methodological approach [19]. The general reverse engineering methodology includes the following major tasks:

- *Seat general analysis*. This includes the collection of all the data that will be useful later on during the creation of the FE model: manufacturer's technical data, reclining positions, pictures, user's manuals…
- *Geometry discretization*. Acquiring all geometric information is probably the most time extensive activity in the process. Since the seats are basically symmetric, only one side was digitized. All components including padding parts and seat covers have been digitized and incorporated to the models. Reinforcements that were considered to have an influence on the deformation or general performance of the seats have also been included.
- *Mass measurement*. The part weight was measured with the help of scales for later density adjustments in the FE model.
- *Thickness* measurement for planar parts.
- *Material model selection and physical properties characterization*. A preliminary analysis of the diversity of materials used in the seat has been performed. Particular material property characterization remains as a future task in this modeling research.

The two convertible seats were shipped by JARI to the NCAC's premises, whose facilities were used to reverse engineer the models. The Royal Automobile Club of Spain provided the infant and booster seats.

In order to acquire the geometry 3.175 mm (1/8 in) masking tape was utilized to define a grid on the components. Once this task is completed, the spatial location of each line intersection was imported into a

PC using a digitizing arm. This device can be described as a portable articulating arm coordinate measuring machine. A computer program enables then the creation of a rectangular or triangular patch or surface every time four points are digitized. Surfaces are displayed in real time in a CAD program. The combination of all patches in the computer results in the virtual representation of the grid defined on the component.

Reference points are defined on the seat and several other components to reproduce the global coordinate system when the digitizing arm or the seat itself has to be moved to have access to hidden parts. The coordinates of the reference points must be read before the arm or the seat is moved. Once the new position is determined, reference points coordinates are fed into the controller program and their spatial new position is digitized, while allows the controller to make coordinate transformation calculations. A non-destructive procedure has been used to disassemble the seat when such action was required to digitize inner parts or reinforcements.

Harness straps have not been generally included in the model, since they have to be adjusted once the human surrogates are positioned in the seat model. However, the crotch strap in one of the convertible seats has been included in the FE model since its geometry is clearly defined between the buckle and the front shield. As it has been explained above, reinforcements in the plastic parts have been digitized and incorporated into the model. The level of detail for the reinforcements is not as fine as for the main parts, since a compromise between simplicity of the model and accuracy of actual mechanical properties has been sought.

Seat covers have also been digitized to enable later addition to the FE model using membrane elements, if desired. Seat covers reproduce the general shape of the seat directly interacting with the occupant. Their shape could also be used as a starting point for simplified models. They also allow for definition of the coefficient of friction between the seat and the occupant. On the other side, since all padding parts can be defined individually with their own skin wrap-ups, the effect of the car cover in the overall performance of the seat is anticipated to be relatively small enough and it could be decided not to include them in the model later during the validation process.

Two different kinds of padding materials have been incorporated to the model. The first one consisting on those separate elements in the actual seats, as opposed to the second kind of padding which can be considered as part of the car cover. In either case the padding has been modeled as an individual part in the computer with its corresponding solid elements. The next picture shows the first kind of padding materials, in the case of one of the convertible seats:

Figure 1. Reverse engineering of a convertible seat (taping for geometry acquisition).

Appendix 1 shows a series of pictures corresponding to all four FE models

CREATION OF FINITE ELEMENT MODELS

Once the digitizing work is complete, IGES files containing the geometry information were imported into MSC/PATRAN release 9.0 [20]. This software, a product of McNeal/Schwendler Corporation, was used to create the FE mesh (namely nodes and elements), connections and parts.

Element nominal side length was chosen to be 15 mm for most of the parts, being 7 mm the minimum value. These values are aimed to represent an equilibrium point among modeling time and involvement, computation demands (time step and calculation time for each step), geometry accuracy and, last but not least, contact performance between the CRS and the vehicle's seat and the human numerical surrogates.

The mesh has been verified for quality and consistency. This includes the equivalence and deletion of unused nodes, the verification of minimum side length, element boundaries and duplicates, element skewness and aspect ratio and element warp angle. Warped elements should particularly be avoided since they constitute a weak spot in the numerical model and may initiate buckling or hourglass parasite. The following element formulations were represented in the models: shell, brick, beam and membrane elements.

All the models have been checked for penetrations between parts. However, the surface offsetting contact algorithm in the solvers may still result in some initial penetrations depending on the contact control cards. Under normal conditions, the solvers can resolve these initial penetrations during the first calculation cycle.

LS-DYNA FE Models

Initially, LS-DYNA input decks [21] were created at the FHWA/NHTSA NCAC. It can be stated that LS-DYNA is the standard explicit solver package in the United States. Six different types of connections available in LS-DYNA were used during the creation of the FE models: spotwelds, nodal rigid body constraints, nodal equivalence, extra nodes, a revolute joint and a spherical joint. The last two types of connection were utilized to realistically represent the degrees of freedom of articulated components in the seats. Spotwelds are the simplest way of rigidly connecting nodes and it has been considered to be a suitable option for the purposes of this modeling effort.

LS-DYNA models included all digitized parts (including padding and seat covers) and models dimensions range from 5,865 nodes, 7,836 elements and 2 parts for the booster seat to 18,204 nodes, 21,345 elements and more than 20 parts for the most complex convertible one. For contact purposes, all solid parts have been “wrapped” in a skin of shell elements with null material (LS-DYNA material type 9). For file management purposes, all reclining positions were included in the same file. In order to select a particular reclining position for a given simulation, instructions are given in the input deck to delete the nodes, the parts and their elements, and the connections corresponding to the rest of positions. Appendix 2 lists the relevant FE model information for all four seats in LS-DYNA format.

The following figure shows the front shield area and its buckle for one of the convertible seats.

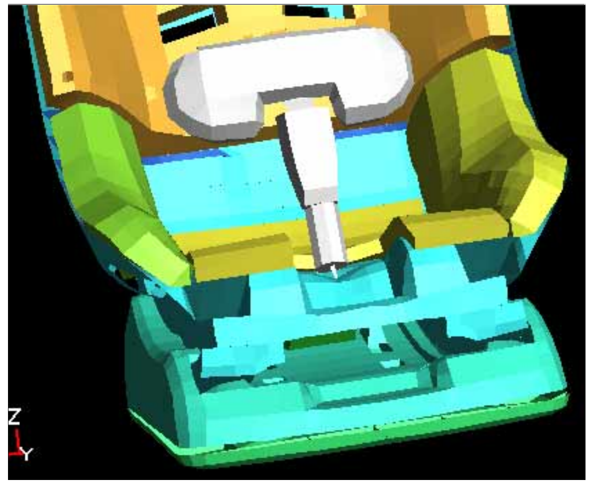

Figure 2. Front shield and buckle area.

In the above picture, the buckle is connected to the main seat plastic shell by means of a steel bar with a virtual spherical joint at the lower tip.

PAM-CRASH FE Models

The Japan Automobile Research Institute utilizes ESI Group PAM-CRASH as primary FE solver package [22]. Preprocessing tasks for PAM-CRASH can be extremely expedite by PAM-SAFE, a tool that offers the modeler useful features for occupant and seat belt modeling and positioning. For these reasons, the original LS-DYNA input decks were translated into PAM-CRASH format using software developed by JARI. During this step non-relevant parts for the initial simulations in PAM-CRASH were deleted from the model (seat cover, skins for solid parts, etceteras). Translation of the input decks included the following tasks:

- Deletion of non-relevant parts.
- Translation of node/element ASCII format.
- Re-creation of connections, including joints.
- Re-creation of joints.
- Re-definition of beam elements (not included in the translation process).
- New material definitions.

Also, densities were adjusted to match actual scale measurement and densities for selected parts were increased to account for deleted parts (i.e., the mass of deleted seat covers was reproduced by increasing the density of the seat plastic shells). Most of the tasks were performed using the preprocessor PAM-GENERIS. Finally, PAM-VIEW was used as post-processor for the preliminary runs.

Two versions of the convertible seats with different back reclining angles were prepared (rear facing and forward facing). Also, in the case of the infant seat two back/head plastic shell positions were created (for the most upright and most horizontal positions). Appendix 2 lists the relevant FE model information for all four seats in PAM-CRASH format.

Material type selection always represents a major challenge during the FE modeling process, especially as far as soft materials are concerned. Several run trials have been performed in PAM-CRASH until an initial satisfactory material behavior was attained for both expanded polystyrene and polyurethane foams. The following table summarizes the choice of material formulations proposed for the simulations:

Table 1.
Suggested material types in PAM-CRASH

Description	**Pam-CRASH type**	**PAM-CRASH definition**
Material for rigid steel bars	Type 81	Rigid
Material for rigid steel shells	Type 100	Rigid
Material for rigid solid elements	Type 99	Rigid
Material for plastic shell elements (Popypropylene)	Type 102	Piecewise Linear Plasticity
Material for generic foam (polyurethane)	Type 21	Elastic Foam w/ Hysteresis
Material for expanded polystyrene foam	Type 20	Closed Cell Foam
Material for rubber elements	Type 11	Blatz-Ko Rubber

Attention was also paid to contact type definition and some preliminary runs were performed to come up with some general recommendations. Point-to-point connections between soft foam parts and more rigid plastic or metal parts is not recommended, since this practice results in stress concentrations that can lead to negative volumes or hourglass appearance. PAM-CRASH contact type 32 (penalty or kinematic tied contact) is proposed between, as an example, the main plastic shell and the foam padding.

Contact type 34 (node to segment contact with edge treatment and 3D bucket search) is suggested for contact between padding/foam parts and impacting plastic/metal parts. Also, contact type 10 (internal solid contact), together with “frozen metric” card can be useful to avoid numerical problems that might arise when solid elements are heavily compressed and distorted: mainly drops in the stable solution time and negative volumes. In the particular case of EPS foam (Expanded Polystyrene), contact type 33 (segment-to-segment contact with edge treatment) was found to behave properly in component simulations between a rigid metal dummy torso and an EPS padding shield part, as shown next:

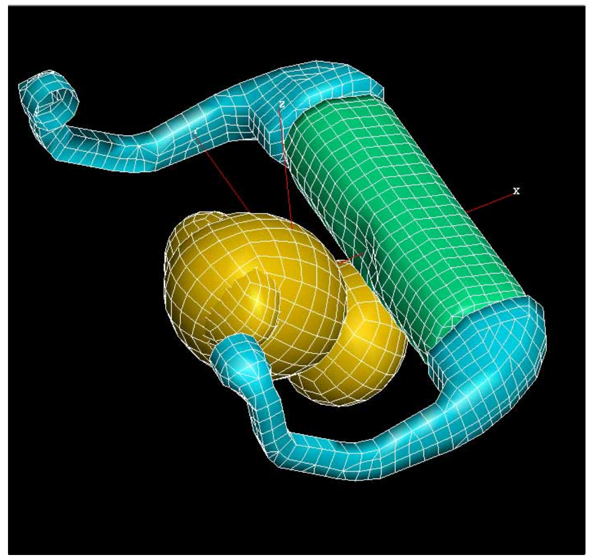

Figure 3. Component simulation for contact type selection (rigid torso against EPS foam shield).

SET-UP FOR INITIAL SIMULATIONS

In order to run the initial simulations that initiated the validation process, it was necessary to develop a FE model of a test bench and incorporate a human numerical surrogate. All three elements –bench, dummy and CRS- had to be combined into a single input deck. This operation was done in PAM-SAFE.

Padding parts have been included in the FE models since it is envisaged that they play and important role in rear-facing simulations. Their role in the frontal deceleration is expected to be much less relevant and for that reason it is suggested to eliminated them during the runs with this seat configuration. As some the preliminary runs show, inclusion of padding materials in the simulation can drastically increase (up to approximately four times) the calculation time that can be attributed to the CRS model elements.

Bench Model

During actual sled tests, bench parts such as the seat and back polyurethane foam play a crucial influence on the kinematics of the CRS and the dummy. In some instances, the CRS almost completely bottoms out the foam and interacts with the aluminum plate in the case of the ECE 44R tests [23]. Subsequently, a remarkable influence on the biomechanical readings of the child dummy can also be expected.

To account for this, a simple test bench FE model was created in PAM-CRASH format consisting on the following parts: seat and back aluminum plates, seat and back foam cushions, supporting bar for rear impact tests and seat belt anchorage points. The following picture shows a general view of this ECE 44R bench:

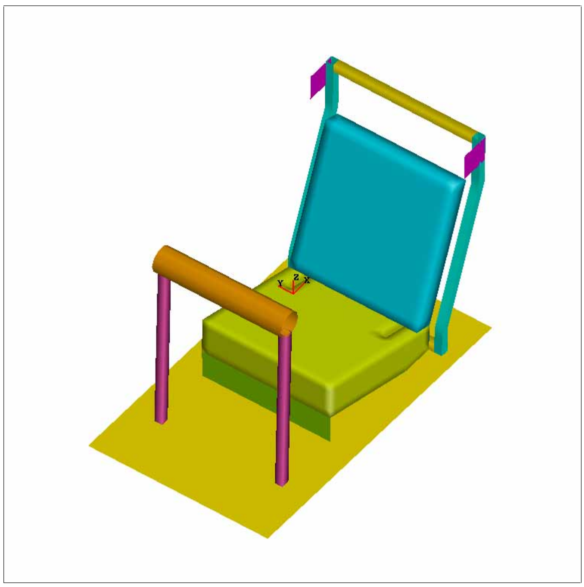

Figure 4. PAM-CRASH model of ECE44R bench.

The test bench FE model consists of 10 parts, 6,235 nodes, 1,497 shell elements and 2,447 solid elements.

P3 Dummy Model

Until on-going child dummy modeling efforts currently carried out at JARI are completed, an ESI P3 dummy rigid model was used for the initial simulations [24]. This dummy is made of 14 rigid body parts modeled with shell elements and articulated through 13 spherical and revolute joints. As prescribed by ECE 44R, its mass is 15 kg. Close to 3,200 nodes and 3,050 shells are the main FE model parameters for this dummy.

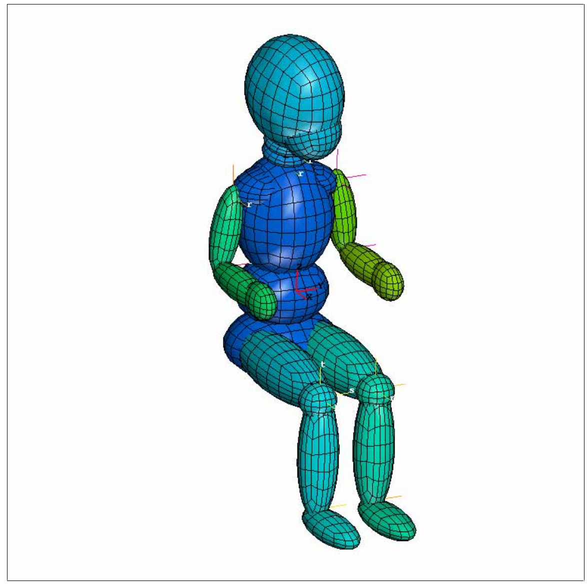

Figure 5. P3 dummy FE model utilized during the initial simulations.

The next picture shows a setup bench/CRS/dummy:

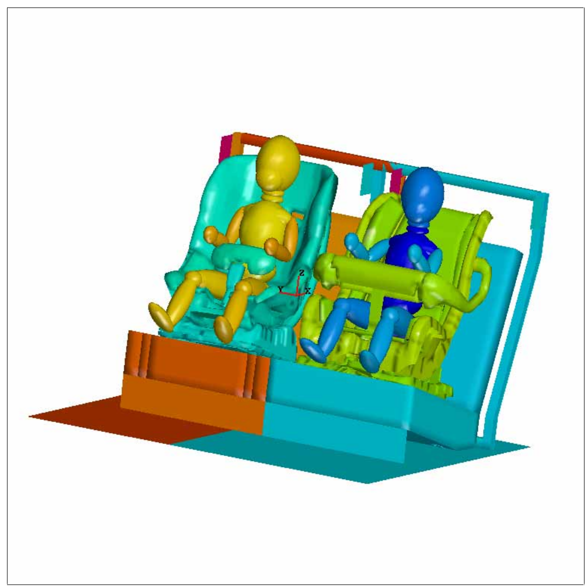

Figure 6. Example of simulation setup.

Validation work is currently being conducted at JARI based on real-life sled tests performed by this research institute.

FUTURE WORK

Future work for this research includes:

- Better polypropylene material characterization. Tensile tests are being conducted at the

FHWA/NHTSA NCAC to obtain material properties for the plastic material used in the CRSs.

- Better foam material characterization. Sphere drop tests are suggested to obtain better material properties both for the polyurethane foam used in the ECE44R bench and in the padding parts.
- Complete validation of the FE model based on available actual sled test results.
- Development of highly detailed child dummy numerical model with deformable parts.

It is also proposed to create facet models of the various CRSs presented in this paper for use in the MADYMO environment. This could enable the coupling of the CRS models with the recent TNO's Q3 rigid body dummy model, which is a front-line candidate to support current research on CRS side-impact regulation proposal and also future investigations on the performance of CRSs during rollover events.

CONCLUSIONS

a) Child passenger protection continues to be an area were more research and collaboration must be encouraged.
b) No worldwide harmonization exists regarding CRS safety standards.
c) Opportunities for increased performance of CRS in frontal (easiness of installation, ISOFIX), side and rollover crashes are substantial.
d) FE method techniques are a valid tool for fostering research in many fields, and also in CRS development.
e) A limited number of FE CRS models were available to the research community.
f) A "fleet" of FE CRS models has been developed in a collaborative research effort between JARI and the NCAC. The fleet consists of two convertible toddler seats, one rear-facing infant seat and a booster seat.
g) FE model sizes range from 5,865 nodes, 4,168 elements and 2 parts for the reduced booster seat to 18,204 nodes, 21,345 elements and more than 20 parts for the most complex convertible one.
h) Details of the FE CRS models and their development process have been explained in this paper.
i) Future work is still need to allow for reliable simulation results.
j) The development of these FE CRS models opens an entire array of simulation possibilities both in an integrated vehicle interior environment and in component or sled test investigations.

RECOMENDATIONS

While as mentioned above 4 out of 5 CRS are misused, a survey carried out in the Northern Madrid metropolitan area concluded that 70 per cent of children under the age of 4 travel with no protection system whatsoever [24]. This situation cries out for increased efforts in the field.

As a means to foster child passenger protection, increased coordination is still needed among the following parties: research community, passenger vehicle manufacturers, CRS manufacturers, vehicle seat manufacturers, consumer representatives and regulatory bodies.

ESV's International Harmonized Research Activities (IHRA) program could consider including after 2001 a new priority research program on Child Passenger Protection to be added to the existing working areas (Biomechanics, Advanced Offset Frontal Protection, Vehicle Compatibility, Pedestrian Impact Protection, Intelligent Transportation Systems and Side Impact). ESV's task group on child passenger protection could coordinate its activities with EEVC's WG 18.

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DISCLAIMER

The responsibility for the results presented here rests entirely with the authors. The conclusions drawn here are those of the authors alone and do not necessarily reflect the views of the NCAC, JARI or any of their sponsors.

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APPENDIX 1. FINITE ELEMENT MODEL ILLUSTRATIONS

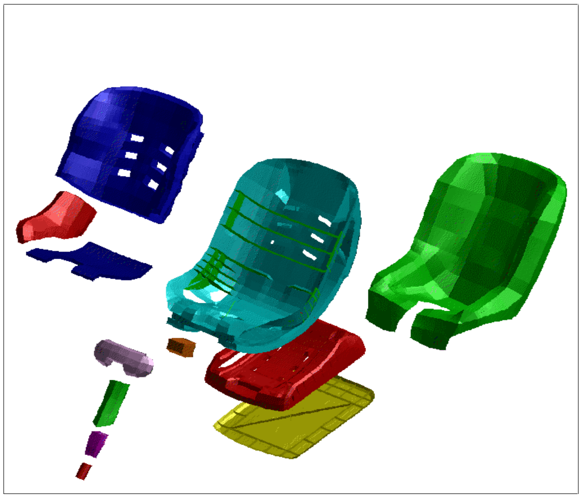

Figure 7. Convertible FE model No. 1 (including all parts).

Figure 8. Convertible CRS FE model No. 2 (including all parts).

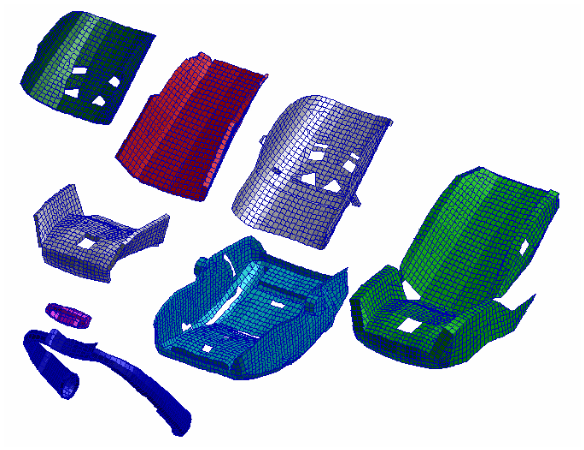

Figure 9. Infant CRS FE model (all parts).

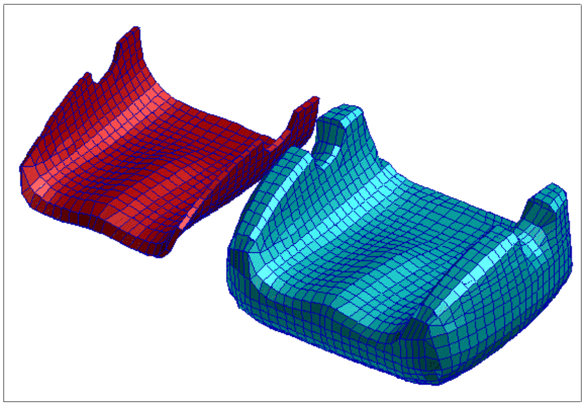

Figure 10. Booster CRS FE model (all parts).

APPENDIX 2. RELEVANT FINITE ELEMENT MODEL INFORMATION

Table 2.
FE Model Data for the Convertible CRS No. 1

Item	LS-DYNA	PAM-CRASH
Parts	26	15
Nodes	17,549	14,019
Beam elements	7	7
Shell elements	16,289	7,812
Solid elements	3,791	3,7918
Total # of elements	20,087	11,610
Spotwelds	28	14
Nodal rigid constraints	0	-
Extra nodes sets	2	-
Joints	1	1
Total # of connections	31	15
Material cards	9	6

Table 3.
FE Model Data for the Convertible CRS No. 2

Item	LS-DYNA	PAM-CRASH
Parts	21	9
Nodes	18,204	14,298
Beam elements	0	0
Shell elements	17,657	9,223
Solid elements	3,668	3,076
Total # of elements	21,345	12,299
Spotwelds	16	16
Nodal rigid constraints	4	-
Extra nodes sets	4	-
Joints	2	2
Total # of connections	26	18
Material cards	8	5

Table 4.
FE Model Data for the Infant CRS

Item	LS-DYNA	PAM-CRASH
Parts	11	7
Nodes	11,124	8,759
Beam elements	0	0
Shell elements	11,104	4,536
Solid elements	1,896	1,896
Total # of elements	13,000	6,432
Spotwelds	27	21
Nodal rigid constraints	4	-
Extra nodes sets	0	-
Joints	0	0
Total # of connections	31	21
Material cards	4	3

Table 5.
FE Model Data for the Booster CRS

Item	LS-DYNA	PAM-CRASH
Parts	4	2
Nodes	5,865	5,865
Beam elements	0	0
Shell elements	3,668	0
Solid elements	4,168	4,168
Total # of elements	7,836	4,168
Spotwelds	4	0
Nodal rigid constraints	0	-
Extra nodes sets	0	-
Joints	0	0
Total # of connections	4	0
Material cards	3	2